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Distribution patterns of vegetation biomass and nutrients bio-cycle in alpine tundra ecosystem on Changbai Mountains, Northeast China

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Abstract: A study was conducted to test the correlation between biomass and elevation and the differences in concentration and storks of nutrients among five vegetation types (Felsenmeer alpine tundra vegetation–FA, Lithic alpine tundra vegetation–LA, Typical alpine tundra vegetation–TA, Meadow alpine tundra vegetation–MA, and Swamp alpine tundra vegetation–SA) on alpine tundra of Changbai Mountains, Jilin Province, China in growing seasons of 2003, 2004 and 2005. The biomass of 43 mono-species and soil nutrients in alpine tundra ecosystem were also investigated. Dominant species from Ericaceae (such as *Rhododendron chrysanthum* and *Vaccinium jliginosum* var. *alpinum*) were taken to analyze organ biomass distribution**.** Result showed that the biomass and elevation had a significant correlation (Biomass=-237.3 ln(Elevation) +494.36; R^2=0.8092; P<0.05). No significant differences were found in phosphorus and sulphur concentrations of roots, stems and leaves among the five vegetation types. There were significant differences in nitrogen and phosphorus stocks of roots, stems and leaves and in sulphur stock of stems and leaves among TA, MA, and SA vegetation types (p<0.05). The nutrient stock of five vegetations was averagely 72.46 kg·hm^{-2}, of which N, P, S were 48.55, 10.33 and 13.61 kg·hm^{-2}, respectively. Soil N and S concentrations in meadow alpine tundra soil type was significantly higher than those in other four soil types (Cold desert alpine tundra soil, Lithic alpine tundra soil, Peat alpine tundra soil, and Gray alpine tundra soil). Phosphorous concentration in SA type was higher (p<0.05) than in other types. Soil nutrient stock (0–20cm) was averagely 39.59 t·hm^{-2}, of which N, P, S were 23.74, 5.86, 9.99 t·hm^{-2}, respectively.

Keywords: Nutrients bio-cycle; Stock; Vegetation type; Soil type; Vegetation biomass

Introduction

The climate change has become one of hotspots in global environmental problems. Future temperature changes in high latitude regions (alpine tundra) are believed to be larger than that in any other part of the globe (Wu *et al.* 2006). Alpine tundra is one of the most sensitive ecosystems to global climate change in the world. However, few studies were done on change of soil carbon stock associated with soil nutrients in temperate alpine tundra ecosystems (Wei *et al.* 2004b). Most of the previous studies focused on tropical areas (de Camargo *et al*. 1999).

The last volcano eruption undergone by alpine tundra on Changbai Mountains, Jinlin Province, China in 1702 constituted a major recurring disturbance and led to the establishment of shrubs or herbs communities. Now alpine tundra on Changbai Mountains is covered with abundant gramineous grasses, low shrubs or sub-shrubs, weeds, moss and lichens (Wu *et al.* 2002). Many studies showed that dominant species affected the vegetation dynamics by modifying their environment in the short- or long-term (Montes *et al*. 2004). The post-volcano successions have mainly been studied from a floristical and structural point of view, whereas less work was done on explaining the vegetation dynamics through biomass or nutrient approaches. For deep understanding of the vegetation dynamics processes of alpine tundra on Changbai Mountains after volcano eruption in 1702, we need detailed information on species biomass, community structure, population dynamics, litter, and soil nutrients dynamics, etc.

Vegetation productivity of alpine tundra is often limited by nutrient availability due to the harsh climate (Turner *et al*. 2004). High vegetation productivity depends strongly on species selection, nutrient availability, nutrient use efficiency, etc. Nutrient limitations are common during plant growth, especially for N and P (Binkley & Ryan 1998). Phosphorous is one of the primary limited nutrients in alpine tundra, although the degree of limitation varies markedly across the heterogeneous tundra landscape (Schmidt *et al.* 1999). For instance, in the North American arctic, NPP in moist tussock tundra tends towards co-limitation by N and P together whereas wet sedge tundra is typically P-limitation (Nadelhoffer *et al.* 2002). Mesic tundra probably tends towards N limitation, although the biological demand for P in all tundra environments is likely to be enhanced by the current low rates of reactive N deposition from the atmosphere (Gordon *et al.* 2001).

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Otherwise, there is increasing evidence that, for number of forests, P is immobile in the first stages of decomposition to a significantly greater extent than N. Furthermore, most plant N was tied into perennial, woody stems or coarse roots and contributed little to the annual cycling of nutrients between plant and soil (Jonasson & Michelsen 1996). Most organically bound nutrients are fixed in the soil and litter and only a low proportion is in biomass in any alpine tundra ecosystem. As in mesic dwarf shrub tundra and in *Betula* and *Salix* dominated shrub tundra, N percentage in soil plus litter increased up to 90%–95% and hence, only 5%–10% of N was incorporated into vegetation biomass (Jonasson & Michelsen 1996). Consequently, although alpine tundra often contains large nutrient pools, these are tied into recalcitrant soil organic matter or, when absorbed by plants, a high proportion is locked into tissue with a slow turnover. It is not surprising, therefore, that alpine tundra productivity is generally nutrients limited and dominant plants are mostly species or functional groups of low nutrient requirement, or species with a conservative nutrient use (Cattle & Crossley 1995; Chapin *et al.* 1995). Most studies of alpine tundra have either addressed the questions of nutrient acquisition or of decomposition and mineralization processes (Ranger *et al*. 1995; Carol *et al*. 2005; Claudine *et al*. 2005) while few studies have attempted to integrate the processes in both biomass and nutrients. There is currently limited information on nutrient cycling of alpine tundra ecosystems whereas it is important to better understand nutrient spatial pattern and potential response of alpine tundra to environmental change in such regions (Laurance *et al.* 1999). Clearly, additional study is needed on biomass and nutrients in alpine tundra and on factors causing natural variability in biomass and nutrients. Investigators often search for relationships between soil or drainage features and vegetation composition (Jose *et al*. 2001; Gastine *et al*. 2003; Marriott *et al*. 2005), but less attention is paid on the effects of soil nutrients on biomass. .

The aim of this research is to (1) examine nutrient concentrations and stocks of vegetation and soil in alpine tundra on Changbai Mountains in which litter has accumulated, as N or P is regarded as the most limited nutrient in vegetation development (Johannisson *et al.* 1999; Piatek & Allen 1999), (2) to study the change of biomass and nutrients, and (3) to test the differences in nutrients among five vegetation types and correlation between biomass and elevation. This work is part of the project, "Biogeochemistry cycling in alpine tundra ecosystem on Changbai Mountains, China", and it could provide information for the effective management and evaluation of the sustainability of alpine tundra ecosystems on Changbai Mountains.

Materials and Methods

Study site

Changbai Mountains Nature Reserve (42°24′N, 128°28′E) is the best-preserved mountainous ecosystem in China, perhaps even in the world, and is a designed UNESCO Biosphere Reserve. The reserve with distinct altitudinal distributions is the most representative upland forest ecosystem, containing wild-ranging types of soils, vegetation and climate. It contains 1337 vascular plant species, including 1250 seed plant species (Xu 1992), and 4 vegetation zones (Shao *et al.* 1996): sub-alpine vegetation, evergreen coniferous forest, mixed broadleaf-conifer forest, and larch forest. The alpine tundra on Changbai Mountains lies in 41°53′–42°04′N, 127°57′–128°11′E between 1950 m and 2690 m amsl and its total area is 15 860 hm^2, of which the area of vegetation coverage is 15 190 hm^2, accounting for 95.78% of the entire alpine tundra area (Jiang *et al.* 2003). The physiognomy mainly consists of volcanic physiognomy, glacier physiognomy and ice edge physiognomy. There are many snow packs on the peak. The mean annual radiation is 506.6 $J \cdot cm^{-2}.a^{-1}$, the mean annual sunlight time 2 295 h, the mean annual temperature -7.4°C, January mean temperature (the coldest month) -23.8°C, July mean temperature (the warmest month) 8.4°C , the highest temperature 19.2°C, and the lowest temperature -44°C. The mean annual precipitation is 900–1340 mm.

The sampling sites are located at elevations from 1950 m to 2650 m on the northern slope of Changbai Mountains (Fig. 1). The area of studied tundra is 15195 hm^2, including five vegetation types, Felsenmeer alpine tundra vegetation(FA), Lithic alpine tundra vegetation (LA), Typical alpine tundra vegetation (TA), Meadow alpine tundra vegetation(MA) and Swamp alpine tundra vegetation(SA), and five soil types, Cold desert alpine tundra soil (CDS), Lithic alpine tundra soil (LS), Gray alpine tundra soil (GS), Meadow alpine tundra soil (MS) and Peat alpine tundra soil (PS).

Sampling

Sampling collection and measurements were conducted in late July and early August of 2003, 2004 and 2005. Sampling sites subjected to minimal anthropogenic disturbances were selected by visual inspection of vegetation. Four transects were randomly allocated with similar aboveground conditions, geomorphic and hydrological conditions. Four sample plots, with size of 0.2 m×0.2 m for each, were set at each altitude along each transect at an interval of 100 m from 1950 m to 2650 m of the altitude. Plants (including roots) were collected with the harvest method at each plot. In total of 43 species were recorded in the harvested plants. Nearly all plant samples were collected in growing season (the most biomass). The soil bulk density was measured at the depths of 5 cm and 15 cm, and the data of soil bulk densities were adjusted for stone content at each vegetation type. Soil samples at each depth of 0–10 and 10–20 cm were collected from each profile to analyze N, P, and S concentrations. In summary, a total of 128 plant samples and 256 soil samples was collected and measured per year.

Chemical analysis and Data

The samples of plants and soils collected were placed in paper envelopes and hop-pockets, respectively, and dried in the sun. These samples were oven-dried at 65°C upon returning to the laboratory. Dried samples were ground into a fine powder using a ball mill for analyzing nutrients. Total N was determined using Kjeldahl procedure followed by colorimetric analysis (Anderson & Ingram 1989) while total P and S using an inductive coupled plasma spectrometry (ICPS) after digestion with $HNO_3/HClO_4$. We used the regression approach to the analysis of variance (ANOVA) in the SPSS statistical software package version 11.0. The significance of effects was tested with the F-ratios between mean squares of effects and residuals. When significant differences were evident, multiple range tests of the least significant differences were conducted.

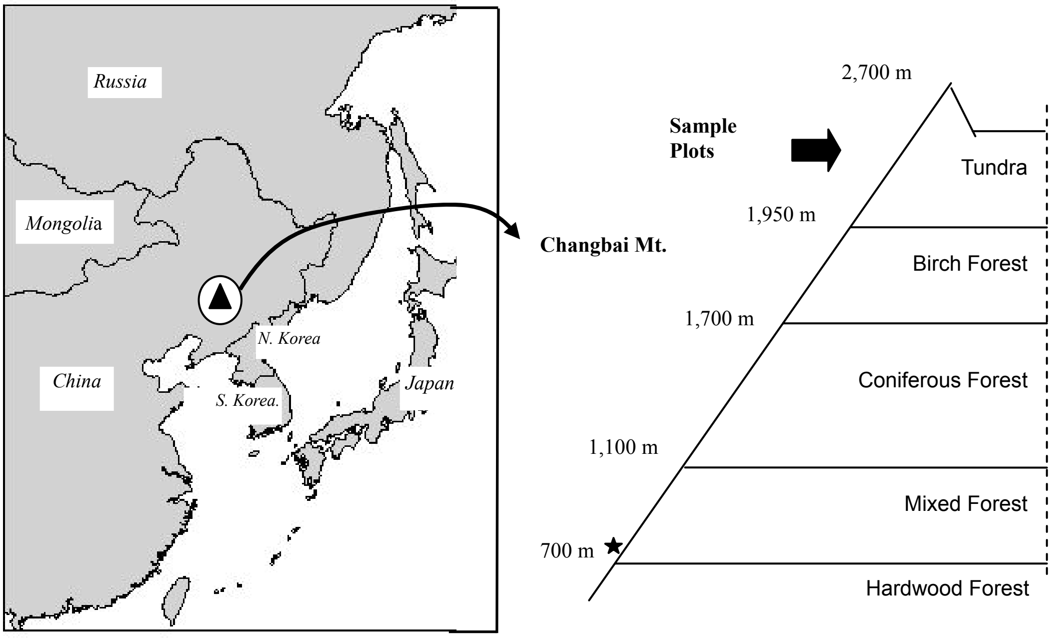

Fig. 1 The sketch of Changbai Mountains Nature Reserve, showing the main vegetation types and sampling plots in tundra.

Biomass and nutrients budget

Using plot biomass and areas of different vegetation types, we could determine vegetation biomass, vegetation carbon storage, and NPP. The biomass of mono-species is calculated by using the following equation (Shao *et al.* 1992):

$$W = (\sum w_j n_j)/1000 \quad (1)$$

Where W is the biomass of mono-species (kg·hm^{-2}), w_j the average dry weight of the j plant species (g·ind.$^{-1}$), n_j the number of j plant species (ind.·hm^{-2}). Using the mean values of nutrients and biomass, we could determine vegetation nutrient pools. Soil nutrient pools (kg hm^{-2}) were calculated using the following equation (Guo & Gifford 2002):

$$P = 100 \times NC \times BD \times D \quad (2)$$

Where NC is the nutrient concentration converted to g·kg^{-1}, BD the soil bulk density (g cm^{-3}), and D is the soil depth in cm. The soil depth measured at this site was 20 cm.

Results

Biomass pattern in alpine tundra

Patterns of vegetation and mono-species biomass

The biomass, either aboveground or belowground parts, was significantly different between FA and LA vegetation types (p<0.05). Root biomass in SA vegetation type was significantly lower than that in TA and MA types, while leaves in SA types was higher than those in TA and MA types, and stem biomass in TA was bigger than that in MA and SA (p<0.05) (Table 1). The biomass of five vegetation types spatially distributes as follows: SA>TA>MA>LA>FA in alpine tundra on Changbai Mountains.

The total biomass and density of investigated 43 mono-species were 2013.2 kg·hm^{-2} and 6.00×10^{5} indivduals·hm^{-2} (Table 2), respectively. The main dominant species are *Rhododendron chrysanthum* (159.01 kg·hm^{-2}), *Vaccinium jliginosum var. alpinum* (137.52 kg·hm^{-2}), *Vaccinium jliginosum* (134.7 kg·hm^{-2}), *Dryas octopetala var. asiatica* (131.5 kg·hm^{-2}), *Salix rotundifolia* (128.4 kg hm^{-2}), *Carex pilosa* (126.09 kg·hm^{-2}), *Carex atrata* (120.01 kg·hm^{-2}), *Rhododendron confertissimum* (98.4 kg·hm^{-2}) in terms of biomass in alpine tundra ecosystem on Changbai Mountains according to the biomass perspective (Table 2), which is similar to the estimation for the important value of species. The average biomass estimated by the method of plot biomass and method of mono-species biomass was 2210 kg·hm^{-2} (Table 1) and 2013 kg·hm^{-2} (Table 2), respectively, with no evident differences. The measurement of mono-species biomass in alpine tundra on Changbai Mountains is the first done, but only 43 plant species was collected and measured in this study, due to the limitation of field investigations and experiments.

Relationship between biomass and elevation

The biomass has significant correlation with elevation (Biomass=-237·ln (Elevation) +494.36; R^2=0.8092; P<0.05), which shows that vegetation biomass is mainly affected by elevation. As shown in Fig. 2, two points were largely deviated from the fitted curve by t-test values (t_{2250m}=3.456; t_{2450m}=4.357, n=7, p<0.05, $t_{standard}$=1.895), which are biomass at both elevations of 2250 m and 2450 m. Field investigation on the spot and analysis demonstrated that the deviated points at the elevations of 2250 m and 2450 m are mainly due to the fact that many dominant species from high elevation (such as LA and FA) are distributed in weather ridge and steep slope at the elevations of 2250 m and 2450 m, but vegetation coverage is below 20%, and that aeolian erosion and snow patch erosion are also strong in somewhere.

Table 1. Vegetation biomass pattern in alpine tundra ecosystem on Changbai Mountains

Vegetation type	Components	Plot biomass ($kg \cdot hm^{-2}$)	Area (hm^2)	Vegetation biomass ($tchm^{-2}$)	NPP ($t \cdot hm^{-2} \cdot a^{-1}$)	Total carbon storage (t)
Felsenmeer alpine tundra vegetation	Belowground	23.82±2.84	85	0.06	0.06	5.1
	Aboveground	36.18±7.18				
Lithic alpine tundra vegetation	Belowground	177.00*±23.91	4160	0.25	0.25	1040
	Aboveground	73.00*±13.81				
Typical alpine tundra vegetation	Root	1160.32±110.80	10870	2.96	1.48	32175.2
	Stem	1204.72*±98.60				
	Leaves	594.96±75.20				
Meadow alpine tundra vegetation	Root	1722.60±110.45	65	2.90	1.45	188.3
	Stem	655.40±98.40				
	Leaves	522.00±32.17				
Swamp alpine tundra vegetation	Root	833.98*±212.70	15	3.22	1.61	48.3
	Stem	753.48±78.30				
	Leaves	1632.54*±213.70				
Total		9389.90	15195	2.21	1.14	33456.9

Note: Mean value and standard deviation of plot biomass are reported. Values behind ± sign are standard deviation. Differences between or among each plant component were tested using a one-way ANOVA with Tukey post hoc test of significance; significance differences at $P<0.05$ are indicated by the asterisk (*).

Table 2. Mono-species biomass of being harvested species in alpine tundra of Changbai Mountains

Species	Biomass [a] ($kg \cdot hm^{-2}$)	Density [b] ($ind. \cdot hm^{-2}$)	Frequency [b] (%)	Species	Biomass [a] ($kg \cdot hm^{-2}$)	Density [b] ($ind. \cdot hm^{-2}$)	Frequency [b] (%)
Dryas octopetala var. asiatica	131.50 ±17.10	5670 ±98.51	100	*Polygonum vivoparum*	0.64±0.12	1000±45.87	25
Vaccinium jliginosum var. alpinum	137.52 ±13.72	6300 ±78.00	100	*Papaver pseudo-radicatum*	11.93±2.78	5300±435.11	12.5
Vaccinium vitis-idaea	71.46 ±7.43	3210 ±34.23	75	*Bepleurum euphorbioides*	22.25±9.01	4500±210.93	25
Rhododendron confertissimum	98.40 ±2.34	4120 ±85.91	100	*Androsace lehmanniana*	4.04±2.10	34200±206.85	25
Salix rotundifolia	128.40 ±5.61	2540 ±72.64	75	*Tilingia tachiroei*	2.85±1.71	12000±103.81	12.5
Rhododendron chrysanthum	159.01 ±11.21	1980 ±48.45	100	*Deyeuxia angustifolia*	2.57±0.98	1700±73.23	12.5
Phyllodoce caerulea	22.06 ±2.33	2010 ±52.67	12.5	*Carex pilosa*	126.09±7.56	188500	100
Vaccinium uliginosum	134.70 ±7.20	7480 ±238.21	62.5	*Carex siderosticta*	3.77±0.12	4000±300.21	12.5
Therorhodion redowskianum	98.20 ±10.21	1700 ±26.73	37.5	*Ranunculus japonicus*	8.09±2.13	20500±123.98	87.5
Saussurea alpicola	54.05 ±1.91	4520 ±472.44	75	*Brachybotrys paridiformis*	50.97±10.68	10800±87.90	87.5
Chrysanthemum zawadsskii f. alpinum	34.83 ±3.92	3100 ±328.27	25	*Jeffersonia dubia*	1.91±0.11	1500±154.1	50
Tofieldia coccinea	3.23 ±0.79	3720 ±126.43	75	*Sanicula rubriflora*	30.48±7.09	40000±2.13	62.5
Lycopodium	10.48 ±2.43	8400 ±178.99	25	*Cardamine leucanthum*	40.4±10.14	25300±498.76	25
Ptilagrostis mongholica	21.56 ±11.21	7300 ±320.11	75	*Hylomecon vernalis*	11.51±2.45	25500±398.12	62.5
Rhodiola sachalinensis	62.50±8.97	2310±34.73	25	*Hieracium coreanum*	12.6±3.65	2340±42.23	62.5
Gentiana jamesii	75.63±3.81	5230±56.76	62.5	*Lloydia serotina*	13.7±17.27	3200±109.78	50
Arctostachylos ruber	71.01±9.78	2300±324.21	50	*Veronica stelleri var. long-istyla*	13.65±2.19	1200±72.89	12.5
Carex atrata	120.01±10.89	200400±702.71	100	*Sanguisorba parviflora*	4.31±3.79	1740±45.24	37.5
Oxytropis anertii	61.77±3.41	7300±32.11	100	*Saxifraga takedana*	3.67±0.89	2130±39.56	25
Carex capollaris	30.14±2.34	20580±107.96	62.5	*Festuca vivipara*	15.09±5.56	1700±23.57	25
Carex laevissima	74.58±10.98	7200±48.95	62.5	*Aquileia japonica*	19.01±4.21	1250±72.11	12.5
Polygonum ochotense	12.63±0.98	3100±21.93	25	/	2013.20	6.00×10^5	/

Note: [a:] 128 sampling plots, Area 20 cm×20 cm; [b:] 32 investigation plots, Area 4 m×4 m; Mean value and standard deviation of mono-biomass and density are reported. Values behind ± sign are standard deviation. The values in frequency column are mean values of some species in alpine tundra of Changbai Mountains.

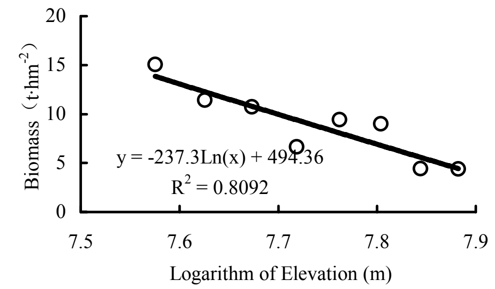

Fig. 2 Relationship between vegetation biomass and elevation in alpine tundra on Changbai Mountains. The T-test showed that two points were largely deviated from the fitted curve. The two points were located at the elevations of 2250 m and 2450 m. The T-test values are 3.456 (at the elevation of 2250 m) and 4.357 (at the elevation of 2450 m) ($n=7$, $p<0.05$, $t_{standard}=1.895$), respectively.

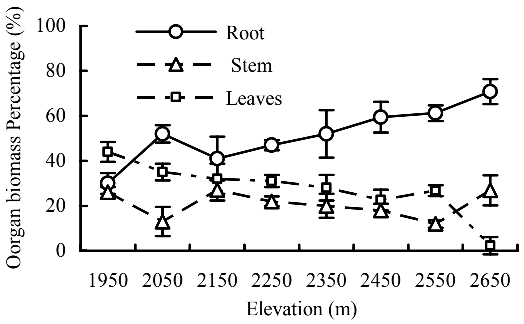

Fig. 3 Gradient change of organ biomass of dominant species (i.e. Ericaceae) along elevation

In order to study the correlativity between organ biomass and elevation, an example of dominant species from Ericaceae (such as *Rhododendron chrysanthum* and *Vaccinium jliginosum* var. *alpinum*) was taken to analyze organ biomass distribution. Different biomass patterns of roots, stems and leaves were found along elevation gradient. With increasing of elevation, the percentage of root biomass increases gradually, the percentage of leaf biomass markedly decreases and that of stem biomass changes irregularly (Fig. 3). Organ biomass of *Vaccinium jliginosum* var. *alpinum,* which is mainly distributed below elevation of 2350 m, distributed along increasing elevation as follows: stems>roots>leaves, and that of *Rhododendron chrysanthum* (mainly distributed above elevation of 2450 m) are as roots> stems> leaves. The subtle difference in organ biomass attributes to long-term adaptation of different dominant species to aeolian or snow erosion.

Vegetation nutrient patterns in alpine tundra

Among the plant components, concentrations of N, P and S in leaves were highest, with N being the major nutrients. No significant differences in P and S concentrations were found among roots, stems and leaves at each vegetation type, but P and S concentrations were at least 1.5–2 times higher in leaves or aboveground than those in roots or belowground (Table 3). Stocks of plant N, P and S in both FA and LA vegetation types, either aboveground or belowground parts, were significantly different ($p<0.05$). There are significant difference in N and P stocks of roots, stems and leaves ($p<0.05$) among TA, MA, and SA while in S stock of stems and leaves (Table 3). The spatial patterns of N, P and S concentrations or stocks of vegetation are relatively similar among the five vegetation types. Nutrient stocks of vegetation was averagely 72.46 kg·hm^{-2}, of which N, P and S is 48.55 kg·hm^{-2}, 10.33 kg·hm^{-2}, and 13.61 kg·hm^{-2}, respectively, in alpine tundra ecosystem on Changbai Mountains (Table 3).

Table 3 The concentrations and stocks of vegetation nutrients in different vegetation types in alpine tundra of Changbai Mountains

Vegetation type	Parts	Total N Concentration (g·kg^{-1})	Total N Stock (kg·hm^{-2})	Total P Concentration (g·kg^{-1})	Total P Stock (kg·hm^{-2})	Total S Concentration (g·kg^{-1})	Total S Stock (kg·hm^{-2})
Felsenmeer alpine tundra vegetation	Below-ground	2.9±1.2	0.07* (0.003)	0.5±0.2	0.01* (0.001)	2.2±1.2	0.05* (0.003)
	Above-ground	10.7±7.8	0.39* (0.056)	1.3±0.3	0.05* (0.002)	1.4±0.2	0.05 (0.001)
Lithic alpine tundra vegetation	Below-ground	5.3±1.4	0.94 (0.033)	2.7±1.6	0.45 (0.04)	1.8±0.8	0.32 (0.02)
	Above-ground	15.2±11.0	1.12 (0.15)	3.8±4.3	0.28 (0.06)	1.3±1.1	0.09 (0.02)
Typical alpine tundra vegetation	Root	5.5±0.5	6.34 (0.06)	0.9±0.4	1.09 (0.04)	1.0±0.6	1.21(0.07)
	Stem	5.0±2.3	6.02* (0.23)	0.9±0.7	1.08*(0.07)	1.5±1.0	1.81*(0.10)
	Leaves	8.2±3.4	4.86 (0.26)	1.2±0.9	0.71(0.09)	2.0±1.2	1.21(0.04)
Meadow alpine tundra vegetation	Root	3.6±1.2	6.2 (0.13)	1.2±0.8	2.07(0.03)	0.8±0.4	1.38(0.12)
	Stem	2.7±1.3	1.77 (0.13)	0.8±0.3	0.52(0.04)	1.7±1.2	1.11(0.03)
	Leaves	6.6±2.1	3.45 (0.07)	1.2±1.1	0.63(0.09)	1.8±0.9	0.94(0.15)
Swamp alpine tundra vegetation	Root	5.4±2.3	4.67* (0.49)	0.5±0.4	0.42*(0.03)	1.1±0.7	0.92(0.09)
	Stem	5.2±1.3	3.92 (0.11)	0.7±0.4	0.53(0.23)	1.9±1.1	1.43(0.34)
	Leaves	5.6±3.6	8.82* (0.78)	1.5±1.1	2.45*(0.97)	1.9±1.6	3.1*(0.57)
Total		/	48.55	/	10.33	/	13.61

Note: Mean value and standard deviation of plant nutrient concentrations or stocks are reported at each component of each vegetation type. Values with parentheses or behind ± sign are standard deviation. Differences between or among each plant component were tested using a one-way ANOVA with Tukey post hoc test of significance; significance differences at $P<0.05$ are indicated by the asterisk (*).

Soil nutrient patterns in alpine tundra on Changbai Mountains

The concentrations and storks of N, P and S in five vegetation or soil types are listed in Table 4. N, P and S in soil are mainly accumulated at the soil depth of 0–10 cm. Nitrogen concentration is higher than that of P and S in all vegetation types. Nitrogen and sulphur concentrations in MA type are significantly higher than those in other four types. Phosphorous concentration in SA type is higher ($p<0.05$) than that in other types. Difference in N concentration throughout the soil layers is not evident ($p<0.05$), but there is a similar pattern between 0–10 cm and 10–20 cm. Phosphorous concentration or stock at the depth of 10–20 cm soil layer is evidently greater than that at the depth of 0–10 cm for FA, LA, TA and MA vegetation types. Sulphur concentration or stock at the depth of 0–10 cm soil layer is evidently greater than that at the depth of 10–20 cm for FA, LA, TA and SA vegetation types. Nutrient stocks in soil of 0–20cm was averagely 39.59 $t\cdot hm^{-2}$, of which N, P and S is 23.74 $t\cdot hm^{-2}$, 5.86 $t\cdot hm^{-2}$ and 9.99 $t\cdot hm^{-2}$, respectively, in alpine tundra ecosystem on Changbai Mountains (Table 4).

Table 4 Soil nutrients concentrations and stocks

Vegetation type	Soil type	Soil depth (cm)	Total N		Total P		Total S	
			Concentration ($g\cdot kg^{-1}$)	Stock ($t\cdot hm^{-2}$)	Concentration ($g\cdot kg^{-1}$)	Stock ($t\cdot hm^{-2}$)	Concentration ($g\cdot kg^{-1}$)	Stock ($t\cdot hm^{-2}$)
Felsenmeer alpine tundra vegetation	CDS	0~10	3.4±0.7	3.33	0.5±0.3	0.46	1.2±0.1	1.18
		10~20	2.2±0.2	2.02	0.6±0.5	0.59	0.8±0.1	0.74
Lithic alpine tundra vegetation	LS	0~10	3.2±0.3	2.62	0.3±0.2	0.24	1.1±0.2	0.90
		10~20	2.4±0.3	1.94	0.3±0.1	0.25	1.2±0.6	0.97
Typical alpine tundra vegetation	GS	0~10	3.2±0.2	2.49	0.8±0.6	0.62	1.1±0.1	0.86
		10~20	2.3±0.2	1.63	0.9±0.4	0.64	1.1±0.4	0.78
Meadow alpine tundra vegetation	MS	0~10	5.4*±1.5	4.10	1.0±0.6	0.76	1.7*±0.4	1.29
		10~20	3.4*±0.3	2.55	1.2±0.3	0.9	3.0*±3.6	2.25
Swamp alpine tundra vegetation	PS	0~10	3.3±1.4	2.05	1.8*±0.3	0.62	1.1±0.3	0.68
		10~20	1.8±0.3	1.01	1.4*±0.6	0.78	0.6±0.1	0.34
Total	/	0~20	/	23.74	/	5.86	/	9.99

Note: Mean value and standard deviation of soil nutrient concentration and stock are reported at different soil depths of each soil type. Values behind ± sign are standard deviation. Differences among each soil depth of different soil types were tested using a one-way ANOVA with Tukey post hoc test of significance; significance differences at $P<0.05$ are indicated by the asterisk (*).

Discussion

Change of vegetation nutrients

Plant N, P and S concentrations or stocks in five vegetation types are summarized in Table 3. Nitrogen mostly concentrates in root parts of TA and SA vegetation types, such as phosphorous in root in MA, or phosphorous in leaves in SA, and sulphur in leaves in SA. On one hand, the differences in nutrient stock among the five vegetation types are due to the fact that different dominant species of five vegetation types and their organs have different selective absorption coefficients to N, P and S nutrients. For instance, *Polygonum ochotense* (main dominant species) has abundant N in TA (0.48%) and SA (0.33%) while *Rhododendron confertissimum* P in MA (0.13%) or SA (0.19%) and *Dryas octopetala* var. *asiatica* S in SA (0.22%) (Wei *et al.* 2004). The other possible reason is that nutrients are probably transferred from aboveground to belowground (roots) during the vegetation development after volcano eruption in 1702. For instance, N and P are mobile in the stem (xylem) and can be relocated within the dominant plants while the S mobility from cell to cell and within the phloem is restricted. This subject needs further study. Joanna *et al.* (2002) reported that root N concentration was 0.90%–1.13% and P was 0.08%–0.12% in sub-arctic and arctic ecosystems and in a *Pinus patula* plantation in South Africa, which is considerably lower than the values reported in this study (Table 3). In this study, we also examined the root nutrient concentrations within the various litter/soil layers, but examined results are disagreement with that of Joanna *et al.* (2002). The possible explanation is that in this study only one time sampling was made for roots during the active growing season of a year. Ideally, roots should be monitored throughout the year to adequately assess biomass, nutrient concentration and uptake.

Change of soil nutrients

The change of soil nutrients occurs after human disturbance or natural disaster. This is mainly because: (1) soil nutrients decomposition and loss are directly affected by human activities and natural disaster; (2) soil moisture is easily affected by climate, e.g., the addition of water to dry soil caused large pulsed of CO_2, NO and N_2O emissions (Davidson *et al.* 1993); (3) pioneer plants or dominant species have different nutrient requirements and nutrient use efficiency as well as store or convert nutrients at different rates (Aerts & Chapin 2000).

Soil N pattern has a close relation with root system distribution (root clumping and root free zone) (Berger *et al.* 2002). Many studies have shown that N-fixing species can significantly increase soil N levels (Chen & Li 2003), while some investiga-

tors reported that there is no correlation between the presence of N-fixing species and total N accumulation in the surface soil (Cromack *et al.* 1999). Aron *et al.* (2001) measured soil nutrient concentrations of *P. aristata* and *P. engelmannii* alpine tundra at the soil depth of 10 cm. Our measurement in soil N concentration in alpine tundra on Changbai Mountains is significantly higher than those in *P. aristata* and *P. engelmannii* alpine tundra (Table 5). In this study we found that surface soil (0–10 cm) in FA and MA vegetation types was of abundant N. The possible explanation is that the plants and litters have a very high N concentration but relatively low N use efficiency (Wei *et al.* 2005), the net N mineralization rate from rock weathering was higher during forming soil after volcano eruption, or that root system in fixing N has special spatial patterns.

Table 5 Comparison of soil N and P concentrations in this study with the data from Aron *et al.* (2001)

Sites	Alpine tundra	N ($g \cdot kg^{-1}$)	P ($g \cdot kg^{-1}$)
P. aristata and *P. engelmannii* alpine tundra (Aron *et al.* (2001)	*P. aristata*	1.6 (0.2)	0.28
	P. engelmannii	2.3 (0.3)	0.35
	Average	1.9 (0.3)	0.32
Alpine tundra on Changbai Mountains	FA	2.7 (0.9)	0.55 (0.41)
	LA	2.9 (0.6)	0.31 (0.21)
	TA	3.1 (0.4)	0.87 (0.57)
	MA	4.8 (1.2)	0.91 (0.66)
	SA	2.9 (0.9)	1.72 (0.73)
	Average	3.28 (1.25)	0.872 (0.780)

Note: Values with parentheses are standard deviation.

Differences in soil P may result from change of biological and geochemical processes at different soil depths after volcano eruption (Frossard *et al.* 1995). Mycorrhizal symbionts and other microorganisms in soil closely couple decomposition and uptake processes contributing to soil P retention. Biological controls on P include root growth patterns, amounts and quality of detritus inputs, extracelluar enzyme activity, production of organic chelates and mycorrhizal activity (Zou *et al.* 1995). Our study showed that soil P is not significantly changed in five vegetation types in alpine tundra on Changbai Mountains. The soil P concentration is lower in LA type while higher in MA at the soil depth of 10–20 cm. So the storage of soil P is large in MA and SA (Table 4). Soil P concentration in alpine tundra on Changbai Mountains is significantly higher than those in *P. aristata* and *P. engelmannii* alpine tundra (Aron *et al.* 2001) (Table 5). Although differences in soil nutrients could be a result of hererogeneous soil conditions, we suggested that a more plausible explanation was that *R. chrysanthwn* and *R. confertissimum* tree line were altering soil chemistry of tundra predominantly by their existence and growth in the alpine tundra environment (Wei *et al.* 2005).

Sulphur is considered as an essential plant macronutrient. The factors controlling the rate of S reduction have not been identified with certainty in the various environments, involving many factors, such as, oxygen and sulphate concentrations, temperature and organic matter availability (Holmer & Storkholm 2001). Soil S comes from the litter mineralization, soil organic matter and rock in alpine tundra on Changbai Mountains. We also found that S and P stocks in dominant plants were very high but relatively low in soil. The high use efficiency of S and P indicated that S and P were the most limited factors for plant growth in alpine tundra on Changbai Mountains (Wei *et al.* 2004). Further research should be done to elucidate the relative contribution of soil S and P during vegetation development after gigantic volcano eruption in 1702. The ratios of C: N, C: P, C: S and C: N: P were often used as indicators of soil nutrient condition (Glazebrook & Robertson 1999; Wei *et al.* 2004a). Soil N and S concentrations are lower in SA while soil P is lower in LA and higher in MA of alpine tundra on Changbai Mountains. The possible reason is that after volcano eruption, soil was mainly oriented with physical weathering. Furthermore, after vegetation restoration, although plants grow slowly under low temperature, the anaerobic and reductive soil protects against decomposition of litter and microorganism, which makes alpine tundra soils abundant in humus or turf bed. Although soil sampling replication is limited in this study, the sampling size satisfied the minimum requirement (5 m× 4 m) in most of ecological field studies by statistical rule of thumb. However, certain cautions are needed when extending the reported findings in this study.

Conclusions

The biomass and its nutrient differences can reflect changes in plant composition. The sampling area, times, depths and harvesting method may account for the fact that there is significant differences of plant plot biomass in both FA and LA (p<0.05); that root plot biomass in SA is significantly smaller than those in TA and MA while leaf biomass in SA bigger than those in TA and MA and stem biomass in TA bigger than those in MA and SA (p<0.05); that soil N and S concentrations in MA are significantly higher than those in other four soil types while P in SA higher (p<0.05).

In order to understand effects of different dominant species on alpine tundra of Changbai Mountains, future comparisons should be specially focused on the role of dominant species in different alpine tundra types, as well as better understanding about general conclusions regarding the spatial pattern of soil nutrients in alpine tundra, which may not hold for cross site comparisons. Although it is still not clear what vegetation in alpine tundra was like during the last glacial maximum, N and P stocks from large Pleistocene dune fields (such as FA, SA) are the evidence that eolian processes are the dominant aspect of Changbai Mountains formation. Future studies should be focused on dominant species shift, spatial-temporal pattern change of biomass and litter, nutrients availability, soil activity, N, S and P re-location and causes of plant or soil nutrient differences in alpine tundra on Changbai Mountains.

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